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THE EFFECT OF TEMPERATURE STRATIFICATION OF A MEDIUM ON TURBULENCE

by

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THE EFFECT OF TEMPERATURE STRATIFICATION OF A MEDIUM ON TURBULENCE

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In a medium with turbulent pulsations of density ρ', being in a field of gravity, a significant role in the dynamics of turbulence is acquired by <u>Archimedean forces</u>; the accelerations created by them are directed vertically and have the value $-g\frac{\rho'}{\rho}$, where ρ – averaged density of medium, g – acceleration due to gravity, and the prime signifies pulsation, i.e., deviation from mean value. In the case of atmospheric air, the consideration of which we will limit ourselves to here, pulsations of density are created mainly by pulsations of temperature and have the form $\rho' = -\frac{\rho}{T}T'$, so that the value of Archimedean accelerations turns out to equal $g\frac{T'}{T}$, where T – average temperature (in sea water the matter is more complicated, since pulsation of density here includes the contribution of pulsation salinity).

During stable (subadiabatic) temperature stratification vertical shifts of air particles, created by turbulence of a dynamic origin, are accompanied by expenditures of energy for work against Archimedean forces and lead to transformation of part of the kinetic energy of turbulence into potential energy of density stratification; consequently, stable stratification weakens turbulence.

During unstable (superadiabatic) temperature stratification Archimedean forces, conversely, create vertical displacements of air particles (at $\rho' < 0$ or $T' > 0$ — upwards, at $\rho' > 0$ or $T' < 0$ — downwards), which leads to an increase of kinetic energy of turbulence at the expense of potential energy of stratification of density; consequently, unstable stratification strengthens turbulence.

For description of turbulence in a temperature-stratified medium a similarity theory was proposed which was founded on the assumption that in a layer with constant stress of friction for height $\tau = \rho u_*^2$ (where u_* — so-called friction velocity) and constant vertical turbulent heat flux q, what is the surface layer of air with a thickness of several dozen meters, all the characteristics of turbulence which are not too small-scaled (do not depend on molecular viscosity and thermal conductivity of air) can depend only on three constant measured parameters — friction velocity u_*, parameter of buoyancy g/T, and "temperature flux" $q/c_p\rho$. A systematic account of this similarity theory is given in Chapter IV of the book [1], where an extensive bibliography is also given.

In this report we will dwell on several separate problems connected with the influence of temperature stratification of the medium on turbulence.

1. Influence of Stratification on the Value of Vertical Turbulent Fluxes on Momentum, Heat, and Moisture

It is known that during unstable stratification and strong wind turbulence is much more intense than during stable stratification and weak wind. We will illustrate this qualitative assertion with some quantitative findings. We will examine a situation, in which the height of roughness of the underlying surface z_0 is considered known and gradient measurements are made on three heights $z = H/2$, H, and 2H. Measured primarily here are the average wind velocity $u = u(H)$, difference of temperatures $\delta T = T(2H) - T(H/2)$, and difference of values of specific humidity $\delta Q = Q(2H) - Q(H/2)$. Then friction velocity u_*, vertical turbulent heat flux q, vertical turbulent moisture flux E (rate of evaporation) according to the above-mentioned

similarity theory can be presented in the form

$$\frac{u_*}{u} = f\left(R, \frac{z_0}{H}\right), \tag{1}$$

$$\frac{-q/c_p\rho}{u\delta T} = \varphi\left(R, \frac{z_0}{H}\right), \tag{2}$$

$$\frac{-E/\rho}{u\delta Q} = \psi\left(R, \frac{z_0}{H}\right), \tag{3}$$

where R — Richardson empirical number, determined by the formula

$$R = \frac{gH}{T}\frac{\delta T}{u^2}. \tag{4}$$

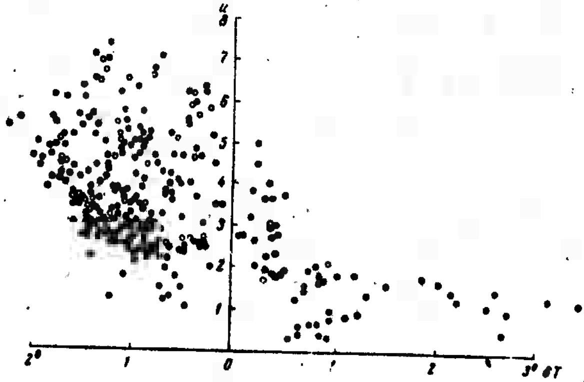
Further for concreteness we will consider that $H = 1$ m and $z_0 = 1$ cm. In cases of strong instability R has a value of the order -0.05, and in cases of strong stability — of the order +0.3 (during neutral stratification, of course, $R = 0$). Theoretical and empirical data concerning functions f, ϕ, and ψ (see [1] and [2]) show that function f, characterizing the ratio u_*/u, during strong instability has a value of around 0.11-0.12, at neutral stratification around 0.09, and at strong stability around 0.06-0.07, so that during instability it turns out to be one and a half or two times greater than during stability. Functions ϕ and ψ change considerably more sharply — with a change of R from -0.05 to +0.3 they decrease by 25 times.

Values $|q|$ and $|E|$ change still more sharply due to the fact that between u and δT (and apparently also between u and δQ) there is a correlation: strong temperature inversions (positive δT) are observed, as a rule, with a weak wind, but during strong instability (negative δT), conversely, there is almost no calm. As an example the figure represents a graph of correlation between u and δT for the period July-September 1959 in the area of Tsimlyansk according to work [3], which indicates that values for the product of $|u\delta T|$ during instability usually ~~a~~re several times greater than during stability (typical example of instability — $u = 6$ m/s and $\delta T = -1.5°$; typical example of strong stability — $u = 0.5$ m/s and $\delta T = 3°$; the product of $|u\delta T|$ here changes by six times). As a result values $|q|$ and $|E|$

during strong instability turn out to be two orders greater than during strong stability, so that the influence of stratification on turbulent heat transfer and passive impurities turns out to be much stronger than its influence on turbulent transfer of momentum.

The strong dependence of values f, ϕ, and ψ on the parameter of stratification R and the presence of a correlation between u and δT (and, apparently, between u and δQ) prevent the calculation of average climatic values of turbulent fluxes of momentum, heat and moisture based on average climatic values u, δT, and δQ with the help of formulas of the type (1)-(3); such a calculation could lead in certain cases to errors of an order of hundreds of percents [3].

Average quadratic pulsations of velocity have values of the order $u_* = uf$ and, consequently, during instability will usually be only several times larger than during stability. Pulsations of temperature have values of the order $T_* \sim \frac{-q/c_p\rho}{u_*} = \delta T \frac{\psi}{f}$, and during instability they will be an order greater than during stability. Let us note that significant pulsations of temperature can appear inside a turbulent layer only due to vertical mixing at averaged potential temperature $\theta(z)$ which is changing with height. At $\theta(z) = \text{const}$, i.e., in the case of neutral stratification, pulsations of temperature will not appear, they can only get into the examined layer from without, for example, in the surface layer of air - from thermal heterogeneities of the underlying suface. But the latter change in the course of twenty-four hours: by day the dark spots are warmer, and at night this is not so. It is possible to think that neutral stratification corresponds exactly to periods of levelling off of thermal heterogeneities of the underlying surface. They during neutral stratification in general there will be no significant pulsations of temperature and, consequently, a situation appears which at the first sight seems paradoxical: during transition from neutral to stable stratification pulsations of temperature should increase, although turbulence (i.e., pulsations of velocity) is suppressed here. These measurements of pulsations of temperature during various thermal stratification show [4] that this curious situation indeed takes place.



Correlation between u and δT for the period June-September 1959.

2. Properties of Symmetry of Turbulence in a Temperature-Stratified Medium

Just as in the case of a temperature-uniform medium it is natural to assume that turbulence in a temperature-stratified medium will be locally uniform. This means that conditional probability distributions for differences of values of hydrodynamic fields in sufficiently close points of space of time, under the condition that rate of movement of the origin of coordinates 0 of the chosen inertial system of reference S coincides with initial Euler speed $u_0 = u(0, t_0)$ at point 0, can depend only on space-time coordinates of points of observation in system S, but do not depend clearly on t_0, x_0, u_0, where x_0 (x_0, y_0, z_0) -- coordinates of point 0 at initial moment of time t_0.

In particular, distributions of probabilities for differences of meteorological elements in close points can clearly depend only on differences of heights of points of observation, and on full height z of one of them can depend only implicity (according to the hypotheses of similarity of A. N. Kolmogorov and A. M. Obukhov – only by means of average velocity, depending on z, of dissipation of turbulent energy ε and average rate of balancing of temperature heterogeneities N).

Inequality of different directions in space, created by the presence of average flow and limiting fluxes of walls manifest themselves on the properties of large-scale components of turbulence, but should not influence the properties of its small-scale components and the local characteristics of turbulence determined by them. However, in a temperature-stratified medium all fluctuations of density, both large-scale and small-scale, will experience the influence of Archimedean forces. Therefore the vertical direction will be assigned for components of turbulence of any scales, and, consequently, turbulence in a temperature-stratified medium cannot be locally isotropic [5]. But it is natural to assume [6, 7] that it will be locally axisymmetrical with respect to vertical, i.e., that the probability distribution for differences will be invariant relative to rotations of the system of coordinates around a vertical axis and specular reflections in any vertical planes.

3. Similarity Hypotheses For Inertially Convective Interval of Turbulence Spectrum in a Stably Stratified Medium

According to the known hypotheses of similarity of A. N. Kolmogorov and A. M. Obukhov, the statistical characteristics of components of turbulence with scales from the so-called inertial interval (small in comparison to external, but large in comparison to internal scale of turbulence) in a case of neutral stratification of the medium can depend only on the two measured parameters ε and N which were mentioned above. According to A. M. Obukhov [8], in the case of a temperature-stratified medium one should add to them the parameter of buoyancy g/T which makes it possible to introduce a new scale of length.

$$L_* \sim \left(\frac{g}{T}\right)^{-3/2} \varepsilon^{5/4} N^{-3/4}. \qquad (5)$$

If this scale belongs to the inertial interval, then in such a case the interval of scales, small in comparison to external, but large in comparison to internal scale of turbulence, can naturally no longer be called simply inertial, but an inertial-convection interval.

In the case of very strong stability a large share of energy of components of turbulence from the inertial-convection interval of the spectrum will be expended for overcoming Archimedean forces, and only a small share will be transmitted to small-scale components, for which viscous dissipation already becomes significant. Besides it is possible to assume that rate of dissipation of energy ε ceases to be significant for conditions of turbulence in the convection interval (constituting the longest wave section of the inertial-convection interval), so that this regimen here is determined only by parameters $\frac{g}{T}$ and N. Then spectral density of energy E(k) and spectral density of heterogeneities of temperature field $E_T(k)$ (where k – wave number) will be determined by formulas

$$E(k) \sim \left(\frac{g}{T}\right)^{2/5} N^{4/5} k^{-11/5}, \tag{6}$$

$$E_T(k) \sim \left(\frac{g}{T}\right)^{-2/5} N^{3/5} k^{-7/5} \tag{7}$$

(Bolgiano [9], Monin [5]). Shur [10] and Lumley [11] proposed another hypothesis for describing the convection interval of the spectrum of turbulence in the case of strong stability, according to which the regimen of turbulence in this interval is determined by the parameter of bucyancy g/T and gradient of average potential temperature Γ, so that

$$E(k) \sim \frac{g}{T} \Gamma k^{-3}. \tag{8}$$

If we take the values of g/T and Γ for characteristic dimension parameters also for the spectrum of temperature, then from considerations of dimension we obtain

$$E_T(k) \sim \Gamma^2 k^{-3}. \tag{9}$$

The strongest difference here is revealed in the spectra of temperature field (7) and (9); unfortunately, so far we do not have experimental data which would make it possible to select one of these spectra and reject the other. Let us note only that spectrum (9) turns out not to be dependent on the parameter of buoyancy, which seems strange. Let us stress, furthermore, that the assumption concerning the dependence of conditions of turbulence in the convection interval of the spectrum on the gradient of average temperature, but not on the gradient of average velocity (entering into the expression of the work created by Reynolds stresses), seems illogical – it is natural to assume that parameters Γ and $\Gamma_u = \partial u/\partial z$ should enter symmetrically into the expressions for statistical characteristics of turbulence.

4. Limiting Instability and Limiting Stability

In description of turbulence in limiting cases of strong instability and strong stability causes a number of disagreements. Let us start with the case of strong instability. According to the previously mentioned theory of similarity the characteristics of turbulence in this case cease to depend on rate of friction u_* and are determined only by the two parameters g/T and $q/c_p\rho$, so that, for example, the gradient of average potential temperature Θ in the surface layer of air turns out to be dependent on height according to the law

$$\frac{\partial\Theta}{\partial z} \sim \left(\frac{g}{T}\right)^{-1/3}\left(\frac{q}{c_p\rho}\right)^{2/3} z^{-4/3} \qquad (10)$$

(although $\partial\Theta/\partial z \to 0$ with increase of z, here it is quite impossible to consider that temperature stratification of medium approaches neutral, since the Richardson number with an increase of z aspires to $-\infty$, and never to zero). On the other hand, Malkus [12] constructed theory of thermal convection, according to which $\partial\Theta/\partial z \sim z^{-2}$ with a proportionality factor depending on the coefficient of molecular thermal conductivity of air (the latter is somewhat strange for turbulence developed during convection; a hypothetical explanation, proposed for cases with the absence of wind and created mainly by wind from horizontal mixing,

involves the influence on ascending convection streams of conditions of their conception in the underlayer of molecular thermal conduction).

Empirical data convincingly show that formula (10) during unstable stratification is justified at least in the layer, in which $0.02 < |z/L| < 1$ (where L – known scale of length, composed of parameters g/T, $q/c_p\rho$, and u_*). However, there are some measurements taken in the atmosphere (Webb) and under laboratory conditions (Thomas and Townsend), according to which at $|z/L| > 1$ formula (10) no longer is confirmed, and perhaps even the conditions $\partial\theta/\partial z \sim z^{-1}$ are established. A discussion of this difference can be found in section 8.2 of book [1], where the corresponding literature is cited. Let us point out, furthermore, the review article by Spiegel [13] and the more recent work of Dyer [14], in which on the basis of the latest, very thorough measurements in Kerang (North Victoria, Australia) a definite conclusion is made in favor of formula (10) both at $|z/L| < 1$ and at $|z/L| > 1$.

Still more difficult is the case of limiting stability. The differences appearing here are formulated most conveniently in terms of the ratio $\alpha = K_T/K$ of coefficients of exchange for heat and for momentum. This value, which at neutral stratification is around a unit, apparently decreases with an increase of stability, and the question arises, does it strive within a limit to a certain positive limit $\alpha_{кр} > 0$ or to zero. The so-called dynamic Richardson number $Rf = \alpha Ri$ (where Ri – ordinary Richardson number) with an increase of stability aspires to a finite limit $Rf_{кр}$. Consequently, in the case $\alpha \to \alpha_{кр} > 0$ the ordinary Richardson number will aspire to finite limit $Ri_{кр}$, and in the case $\alpha \to 0$ will increase without limit. In the first of these cases according to the similarity theory ([1], point 7.3) the gradient of temperature $\partial T/\partial z$ will asymptotically approach a constant

$$\frac{\partial T}{\partial z} \sim \frac{1}{\alpha_{кр} Rf_{кр}} \frac{g}{T} \left(\frac{q}{c_p \rho u_*} \right)^2, \qquad (11)$$

so that temperature will <u>increase linearly with height</u>; in the second case temperature will increase with height more rapidly than by linear law.

Speaking in favor of the assumption $\alpha \to \alpha_{\text{кр}} > 0$ are the observations of Liljequist [15], who detected linear profiles of temperature, corresponding to formula (11), during strong inversions in Antarctica, and the results of processing the empirical findings of various authors by A. B. Kazanskiy [16], according to whom $Ri_{\text{кр}} < 0.3$. Let us mention also our works [7] and [17], in which with the help of simplified Friedman-Keller equations for single-point second moments of velocity of wind and temperature we obtained the dependence of α on Rf, leading to the limiting value $\alpha_{\text{кр}} > 0$ (in an example from [17] $\alpha_{\text{кр}} \approx 0.2$ and $Ri_{\text{кр}} \approx 0.3$).

On the other hand, there are certain measurements in nature (J. Taylor-Prowdmen; Kolesnikov) and in the laboratory (Ellison and Turner), a discussion of which can be found in section 8.2 book [1], which are in qualitative agreement with the formula of Ellison

$$\alpha = \alpha_0 \frac{1 - Ri/Ri_{\text{кр}}}{(1 - Rf)^2} \to 0 \quad \text{when} \quad Ri \to Ri_{\text{кр}} \tag{12}$$

(the conclusion of which is based, it is true, on much rougher simplifications of Friedman-Keller equations than those which are used in [7] and [17]). Based on these findings $Rf_{\text{кр}} \approx 0.10\text{–}0.15$ and $\alpha \approx 0.02\text{–}0.05$ at $4 < Ri < 10$.

For the solution of this difference in the values of $\alpha_{\text{кр}}$ and $Ri_{\text{кр}}$ the further accumulation of findings concerning turbulence under conditions of very strong stability is necessary. Besides one should consider that under such conditions turbulence is apparently concentrated in areas which are randomly distributed in space and with vertical dimensions which are much less than horizontal. Inside such regions turbulent mixing leads to vertical temperature balance (more exactly – potential temperatures), and outside their temperature can change very sharply with height. As a result instantaneous

profiles of temperature can have numerous randomly distributed breaks, and only a sufficiently wide averaging will lead to smooth average profiles of temperature, perhaps of the form (11). Under such conditions it is expedient not to be limited to a determination of only average profiles, insufficiently characterizing the structure of turbulence, but, by following methods of describing alternating turbulence for the borders of turbulent boundary layers, trails, and streams, to determine, for example, the field of "coefficient of intermittence," i.e., the probability of the presence of turbulence in different points of space.

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ABSTRACT

(U) The following problems associated with the effect of temperature stratification on turbulence are discussed: 1) the effect of stratification on the vertical turbulent fluxes of momentum, heat and moisture; 2) the symmetric properties of turbulence in a temperature stratified medium; 3) similarity hypotheses for the inertially convective interval of turbulence spectrum in a stability stratified medium; 4) the limiting cases of instability and stability. The influence of temperature stratification and turbulence is described with the aid of three parameters-the buoyancy parameter, the friction velocity and the so-called "temperature flux". Orig. art. has: 1 figure, 12 formulas.